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MONOPOLE CATALYZED NUCLEON DECAY: THE ASTROPHYSICAL CONNECTION*

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Abstract

If monopoles catalyze nucleon decay, limits on the product of the monopole flux and the catalysis cross section may be placed from "astrophysical" considerations. We review these limits and discuss their reliability.

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One of the most remarkable developments in monopole physics over the past few years has been the observation by Callan¹ and Rubakov² that the monopole-fermion system opens a low-energy window to short-distance physics. In particular, they have demonstrated that for the massive magnetic monopoles expected in grand unified theories, $m_M \sim 10^{16}$ GeV, low-energy monopole fermion scattering could violate baryon number with a cross section on the order of a strong cross section.

The non-conservation of baryon number in the presence of a monopole results in monopole "catalysis" of nucleon decay. The nucleon lifetime in the presence of a monopole is very short compared to the usual GUT proton lifetime of $\sim 10^{31}$ years. In the presence of a monopole, nucleons decay at a rate³

$$\Gamma = n_N \sigma_{\Delta B} |v| \quad (1)$$

where n_N is the nucleon density, and $\sigma_{\Delta B}$ is the cross section for monopole nucleon scattering with concomitant nucleon decay. Since the rate is proportional to the nucleon density, the first guess for a place to look for an astrophysical effect is where the nucleon density is high. A good candidate for such a location is the interior of a neutron star.

Neutron stars are objects of roughly 1 solar mass (2×10^{33} g) at nuclear matter density ($\rho \sim 3 \times 10^{14}$ g cm $^{-3}$).⁴ In the neutron star the monopole converts the rest mass of the nucleon into relativistic particles, releasing energy at a rate

$$\begin{aligned} L_M &= m_N n_N \sigma_{AB} |v| \\ &= 8.5 \times 10^{18} \sigma_O |v| \text{ erg s}^{-1} \text{ monopole}^{-1}, \end{aligned} \quad (2)$$

where we have defined σ_O by

$$\sigma_{AB} = \sigma_O 10^{-27} \text{ cm}^2. \quad (3)$$

If catalysis proceeds at a strong rate, $\sigma_O \approx 1$.

The relative velocity appearing in eq. (2) is of the order 0.1 - 0.3, which is the Fermi velocity of the nucleons in the neutron star. One might naively expect for the exothermic decay reaction $\sigma_{AB} \sim |v|^{-1}$, but it has been pointed out⁵ that the situation, at least for low relative velocities, may be much more complicated. In this paper I will discuss limits on $\sigma_O |v|$ for values of $|v|$ from $|v| \sim 1$ (in neutron stars) to $|v| \sim 10^{-5}$ (in the earth). When comparing limits, it should be remembered that the direct comparison of limits for very different values of $|v|$ may be dangerous. I should also note that catalysis of nucleon decay in neutron stars is closer to the "high-energy" regime where the calculations are more reliable than catalysis in detectors on earth where $|v| \lesssim 10^{-3}$.

The total energy released by the monopoles in the neutron star is proportional to the number of monopoles in the star. A terrestrial monopole hunter doesn't care about limits on the number of monopoles in neutron stars, but about the inferred limits on the galactic monopole flux. Unless there is some unexpected physics in the interior of neutron stars, the limit on the number in the star can be simply related to the monopole flux. Jeff Harvey discusses the possibility of unexpected physics in these proceedings.⁶

If we assume that all monopoles once captured by the neutron star are present (i.e. no $M-\bar{M}$ annihilation or ejection of monopoles⁶), the total number of monopoles in the neutron star is given by

$$N_M = \pi F_M A_c \tau f \quad (4)$$

where F_M is the monopole flux, A_c is the capture area of the neutron star, τ is the age of the neutron star, and f is the fraction of monopoles incident on the neutron star which are captured. The capture area of the neutron star is larger than the geometrical area by a factor

$$\frac{A_c}{A_{NS}} = \frac{1 + 2M_{NS}G/v_M^2 R_{NS}}{1 - R_S/R_{NS}}, \quad (5)$$

$$\approx 4 \times 10^5 \quad (v_M = 10^{-3})$$

where M_{NS} and R_{NS} is the mass and radius of the neutron star, v_M is the incident monopole velocity, and R_S is the Schwarzschild radius of the star. The neutron star has $M_{NS} \approx 1$ solar mass, $R_{NS} \approx 10$ km, and the initial velocity of the monopole should be a typical virial velocity of $10^{-3} c$.

The initial monopole energy is $E_0 = mv_M^2/2 = 5 \times 10^9 (m/10^{16} \text{ GeV})(v_M/10^{-3}c)^2 \text{ GeV}$. When the monopole hits the neutron star⁷, it will have been accelerated to the escape velocity of the neutron star, $v_{esc} \sim 0.3 c$. If the monopole loses energy greater than E_0 , it will eventually become trapped in the star. In scattering with electrons, the monopole suffers an energy loss of

$$\begin{aligned} dE/dx &\approx 4\pi^2(n_e/p_e)|v|, \\ &\approx 10^{11} |v| \text{ GeV cm}^{-1} \end{aligned} \quad (6)$$

where n_e is the electron density ($\sim 10^{36} \text{ cm}^{-3}$), and p_e is the electron Fermi momentum ($\sim 50 \text{ MeV}$). Therefore for $|v|$ greater than escape velocity, the monopole will lose enough energy to become bound after traversing less than a centimeter. (It is not necessary for the monopole to be completely stopped in the first pass through the star, as long as it has lost enough energy to become gravitationally bound.) In addition to energy loss in electron collisions, there are additional energy loss mechanisms of less importance, but still sufficient to capture the monopole.⁸ Therefore we will

assume the fraction of incident monopoles captured by the neutron star f , is one. For $f = 1$, the number of monopoles in the neutron star is related to the galactic flux by

$$N_M = 5 \times 10^{20} F_{16} \quad , \quad (7)$$

where we have defined F_{16} as

$$F_{16} = F_M / 10^{-16} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad . \quad (8)$$

The luminosity of the neutron star due to monopole catalyzed nucleon decay will be

$$\begin{aligned} L^T &= N_M L_M \\ &= 8.5 \times 10^{18} N_M \sigma_O |v| \text{ erg s}^{-1} \text{ monopole}^{-1} \\ &= 4 \times 10^{39} F_{16} \sigma_O |v| \text{ erg s}^{-1} \quad . \end{aligned} \quad (9)$$

We will now discuss ways of limiting the luminosity of neutron stars, hence placing limits on $N_M \sigma_O |v|$ and $F_{16} \sigma_O |v|$.

Old neutron stars should be quite numerous in the galaxy. Published estimates of the density of old ($\tau \sim 10^{10}$ years) neutron stars range from $n_* = 10^{-1}$ to $n_* = 4 \times 10^{-3} \text{ pc}^{-3}$.⁹ The HEAO II "Einstein" observatory is capable of seeing neutron stars with a luminosity of $10^{31} \text{ erg s}^{-1}$ at a distance of 100 pc. Beyond 100 pc, absorption by the

interstellar medium prevents observation of a luminosity as low as 10^{31} ergs $^{-1}$. The surface density as low as old neutron stars within 100 pc is

$$\sigma \sim 0.4 \left(\frac{n_*}{4 \times 10^{-3} \text{ pc}^{-3}} \right) \text{ deg}^{-2}, \quad (10)$$

or about 1 neutron star every 2.5 Einstein pictures. There have been surveys of "serendipitous" sources which cover $\sim 50 \text{ deg}^2$ of sky and see no "blank field" x-ray sources.¹⁰ We may interpret this lack of observation as evidence that the luminosity of old neutron stars is less than $10^{31} \text{ erg s}^{-1}$.¹¹ This limit is subject to two major uncertainties. If the number density of old neutron stars is an order of magnitude smaller than the lowest published limit, then an area of 50 deg^2 might only contain 1 or 2 sources. Therefore this limit is extremely sensitive to n_* . The second problem is that the surveys might have discriminated against sources with photon energy as low as expected from a 30 eV blackbody (the temperature of a neutron star with luminosity of $10^{31} \text{ ergs}^{-1}$). In order to answer these uncertainties a proposal has been made to perform a survey to cover a much larger area, and to look specifically for sources of low-energy photons.¹²

A second way to limit the luminosity of old neutron stars is to consider their effect upon the x-ray background. This was done in ref. 11 by using the Silk limit, which is a limit on the total power radiated during the lifetime of the neutron star. The limit $P(E > 0.2 \text{ keV}) \leq 6 \times 10^{49}$ ergs over the lifetime of the neutron star results in a limit of $L^{\gamma} \leq 2 \times 10^{32} \text{ erg s}^{-1}$ on the luminosity of old neutron stars. A similar bound may be found by calculating the present UV and x-ray flux from the old neutron stars in the galaxy and comparing it to the measured background. This method was used in ref. 13, and resulted in a limit $L^{\gamma} \leq 3 \times 10^{30} \text{ erg s}^{-1}$ on the luminosity of old neutron stars. However, this calculation did not consider the absorption of the photons by the interstellar medium. Recently there has been a better measurement of the soft x-ray background¹⁴. This observation is really four independent measurements of the flux in different energy bands, which in principle gives four independent limits on the luminosity of old neutron stars. This recent measurement has been used to limit the luminosity of old neutron stars after including corrections for absorption by the interstellar medium.¹⁵ The limits found were $L^{\gamma} \leq 1.4 \times 10^{32} \text{ erg s}^{-1}$, $L^{\gamma} \leq 9.7 \times 10^{31} \text{ erg s}^{-1}$, $L^{\gamma} \leq 1.8 \times 10^{32} \text{ erg s}^{-1}$, and $L^{\gamma} \leq 5.6 \times 10^{32} \text{ erg s}^{-1}$ for the four energy bands measured. The above limits are limits on the total photon luminosities from the energy flux in different energy bands. Although the background limits are

not as good as the serendipitous limit, they are not as sensitive to n_* . The flux from the background sources, hence the luminosity limit, is linear in n_* . If n_* is a factor of 10 smaller than expected, then the limit from the background is a factor of 10 higher, while the limit from the serendipitous sources may disappear altogether.

The above limits are on the photon luminosity, and to obtain limits on the total luminosity, it is necessary to correct for neutrino emission. The relationship between the observed limit on the photon luminosity, and the inferred limit on the total luminosity depends upon the equation of state and the structure of the neutron star. In Figure 1, several examples of the conversion from photon to total luminosity are given. The curves π^a and π^b are equations of state with pion condensates, while the curves BPS, PS, I, II, IIB, III, A, B are equations of state without pion condensates.¹⁶ For most models a lower photon luminosity results in a lower ratio of L^T/L^Y . Most corrections have been made using the π^a curve as the best model. Using the π^a curve the limit from serendipitous sources, $L^Y \lesssim 10^{31} \text{ erg s}^{-1}$ translates into a limit on the total luminosity of $10^{33} \text{ erg s}^{-1}$. Using eq. (9) this results in the limits $N_{M^0_0|v|} \lesssim 10^{14}$ and $F_{16^0_0|v|} \lesssim 2.5 \times 10^{-7}$. The limit from the background flux, $L^Y \lesssim 10^{32} \text{ erg s}^{-1}$ translates into a limit on L^T of $10^{36} \text{ erg s}^{-1}$, or $N_{M^0_0|v|} \lesssim 10^{17}$ and $F_{16^0_0|v|} \lesssim 2.5 \times 10^{-4}$. With the prejudice that π^a is the best equation of

state, an improvement of an order of magnitude in L^Y resulted in a difference of 10^3 in the flux limit.

There is a window of vulnerability in the above arguments. If the catalysis proceeds quickly enough, the neutron star might be completely eaten in a time less than the age of the galaxy.¹⁷ The rate of nucleon decay is

$$R_M = 8.5 \times 10^{21} \sigma_0 |v| \text{ s}^{-1} \text{ monopole}^{-1} , \quad (11)$$

and the number of monopoles in the neutron star after a time t is

$$N_M = 2 \times 10^3 F_{16} t(\text{sec}) . \quad (12)$$

Therefore the number of nucleons that have been eaten in a time t is

$$\begin{aligned} N &= \int_0^t R_M N_M dt \\ &= 8.5 \times 10^{24} F_{16} \sigma_0 |v| t^2, \end{aligned} \quad (13)$$

where t is in seconds. The monopoles will eat the neutron star ($N = 10^{57}$) in a time

$$t = \frac{4 \times 10^9}{(F_{16} \sigma_0 |v|)^{1/2}} \text{ years}, \quad (14)$$

Therefore if $F_{1600}|v| \gtrsim 10^{-3}$, monopoles will eat the neutron star in an age less than the age of the galaxy, and limits on the luminosity of old neutron stars cannot be used to limit the monopole flux.

There are several ways to close the window of vulnerability. It is not at all clear that the neutron star will sit around quietly as it is eaten. There should be an instability in the neutron star when its mass becomes less than about half its initial mass. This instability might result in a neutron star explosion. The details of this explosion have not been worked out, but it might be suspected that such events are ruled out. Another way to close the window of vulnerability is to look at known pulsars.

There exist many nearby ($d \lesssim 100$ pc) young (spin-down age $\sim 10^7$ years) pulsars that have limits on their luminosity. One such example is PSR 1929+10, which is a 3×10^6 yr old pulsar at a distance of ~ 60 pc, and a maximum luminosity of 3×10^{30} erg s $^{-1}$. This pulsar has been used¹⁸ to limit $N_{M00}|v|$ to be less than 3.5×10^{11} . For a neutron star of age $3 \times 10^{-4} \tau_{\text{GALAXY}}$, $N_M = 10^{17} F_{16}$. This results in the limit $F_{1600}|v| \lesssim 2.5 \times 10^{-6}$. This limit is an order of magnitude less stringent than the serendipitous bound, but has several advantages. It is insensitive to the assumption of the number density of old neutron stars. For the π^a equation of state, there is negligible L^T/L^Y correction for

this low luminosity. Finally it closes the window of vulnerability discussed above. It does depend on the assumed distance to the pulsar and the assumed age of the pulsar. In the analysis a distance of 60 pc was assumed, but a recent measurement has it as far away as 250 pc,¹⁹ in which case the limit on L^γ would be 5×10^{31} erg s⁻¹, which due to neutrino emission (using π^a) results in a limit of 5×10^{34} erg s⁻¹. This results in the limits $N_{M^0O}|v| \lesssim 6 \times 10^{15}$, and $F_{16^0O}|v| \lesssim 4 \times 10^{-2}$. The true distance to PSR 1929+10 is probably somewhere in between the above extremes. At any rate, there are several other "nearby" pulsars with similar luminosity limits, and the limits from known pulsars are more reliable than the limits from (unseen) unknown pulsars, and it is worth paying the price of having $\tau/\tau_{\text{GALAXY}}$ fewer monopoles than in the old neutron stars.

The observation of known pulsars is particularly interesting if we relax the assumption that the only monopoles in the neutron star have been accreted during the neutron star phase. It is believed that massive stars were the progenitors of neutron stars, and recent estimates of the number of monopoles captured in the pre neutron star stage is²⁰ $N_M \approx 10^{22} F_{16}$, independent of the age of the neutron star. In this case, the limit $N_{M^0O}|v| \lesssim 3.5 \times 10^{11}$ from PSR 1929+10 results in $F_{16^0O}|v| \lesssim 3.5 \times 10^{-11}$.

Neutron stars are not the only condensed objects where monopole catalyzed nucleon decay might be important. If there were 4×10^{19} monopoles in white dwarfs, the white dwarf luminosity would be about $10^{30} \text{ erg s}^{-1}$.²¹ Remarkably, there are no observations of white dwarfs with luminosity below $10^{30} \text{ erg s}^{-1}$.²² This results in the limit $F_{16^0} |v| \lesssim 2 \times 10^{-4}$.²¹ There are several uncertainties in the above arguments. It is yet to be demonstrated that M-M annihilations do not reduce the number of monopoles in the white dwarfs. Possible nuclear suppression factors have not been considered, and since the relative velocity of the monopole - nucleon systems may be small, and the interior of the white dwarfs contain spinless nuclei, there may be a suppression of $10^{-2} - 10^{-6}$.⁵ Finally if the interior of the white dwarf is hot enough, neutrino emission may increase in importance. However, the possibility of monopoles keeping white dwarfs hot is interesting, as it may answer the old astrophysical question "where are the dim degenerates?"

There is another limit on monopole catalyzed nucleon decay from everyone's favorite astrophysical object -- the earth.²³ Monopoles in the earth release energy through catalysis at a rate

$$\begin{aligned} L_M &= n_N \sigma_0 |v| \\ &= 5 \times 10^4 \sigma_0 |v| \text{ erg s}^{-1} \text{ monopole}^{-1}, \end{aligned} \quad (15)$$

for $\rho \sim 3 \text{ g cm}^{-3}$. The limit on the luminosity of the earth $L_\oplus \lesssim 10^{20} \text{ erg s}^{-1}$, implies $N_M \sigma_0 |v| \lesssim 2 \times 10^{15}$. The number of

monopoles captured by the earth is given by eqs. (4) and (5) using the earth radius and mass:

$$\begin{aligned} N_M &= \pi F_M A_c \tau f_\oplus \\ &= 2 \times 10^{20} F_{16} f_\oplus, \end{aligned} \quad (16)$$

where f_\oplus is the fraction of incident monopoles captured in the earth. In neutron stars, f is 1, but in the earth only monopoles with velocities less than about $3 \times 10^{-5} (m/10^{16} \text{ GeV})^{-1}$ will be trapped²³, assuming $dE/dx = 30 \text{ GeV cm}^2 \text{ g}^{-1} \beta \rho$, where β is the monopole velocity and ρ is the density in the earth.²⁴ If the local flux of monopoles has a velocity typical of the galactic virial velocity, $v_M = 10^{-3}$, then $f_\oplus \approx 10^{-6} (m/10^{16} \text{ GeV})^{-4}$. If the local flux of monopoles has a velocity typical of the escape velocity from the sun, $v_M \approx 10^{-4}$, then $f_\oplus \approx 10^{-3} (m/10^{16} \text{ GeV})^{-4}$. Therefore the limits from earth heat are²³

$$\begin{aligned} F_{16} \sigma_0 |v| &\leq 10^{-5} / f_\oplus \\ &\lesssim \begin{cases} 10 (m/10^{16} \text{ GeV})^4 & (v_M = 10^{-3}) \\ 10^{-2} (m/10^{16} \text{ GeV})^4 & (v_M = 10^{-4}) \end{cases} \end{aligned} \quad (17)$$

A similar analysis has been done for Jupiter,²³ with the result $F_{16} \sigma_0 |v| \lesssim 5 \times 10^{-3}$ for $v_M = 10^{-3} \sim 10^{-4}$. Finally, it should be remembered that this limit may be susceptible to the low velocity suppression of the cross section.

The conclusions of the talk are given in Table 1. I think it would be worthwhile to repeat the uncertainties in the individual limits. It also should be remembered that quoted flux limits (except for the earth limit) are for typical galactic fluxes. If one believes the local flux is enhanced, it is necessary to make a correction to get the limit on the local flux. It is also dangerous to compare limits with different relative velocities.

All neutron star limits have the uncertainty of possible $M-\bar{M}$ annihilations reducing the number of monopoles. All the neutron star limits have used the π^a equation of state to correct for neutrino emission. If one uses the π^b equation of state, the L^T/L^Y correction would be about 10^3 for all the neutron star limits. The serendipitous limit is very sensitive to n_* , and if n_* is an order of magnitude smaller than expected, it is useless. The background limits are linear in n_* , but depend on absorption by the interstellar medium (ISM). The limit in ref. 13 did not correct for absorption, and the limit on L^Y is probably too severe. The limits from young neutron stars depend on estimates of their age and distance. The limit on the monopole flux if we include main sequence capture is very good, but it assumes an evolutionary history for the neutron star progenitor, it assumes that monopoles do not annihilate, and it assumes that monopoles were not expelled in the formation of the neutron star. The limit from white

dwarfs requires more work before the uncertainties are settled. The limits from the Earth and Jupiter are sensitive to the monopole mass. If the mass is much larger than 10^{16} GeV, it is harder to capture the monopoles, and the flux limit is relaxed.

Terrestrial detection of monopole-catalyzed nucleon decay would be a remarkable discovery. It seems impossible in the near future if $F_{16\sigma_0}|\nu|$ is much less than one. In Table I are several astrophysical arguments that suggest that $F_{16\sigma_0}|\nu|$ is much less than one. Although there are uncertainties that might reduce any of the limits in Table I by a factor of 10 or so, it would seem unlikely that the independent astrophysical uncertainties conspire to remove all the limits to allow $F_{16\sigma_0}|\nu| \gtrsim 1$.

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Table I

Astrophysical Limits on Monopole Catalysis

OBJECT	$ v $	$L^\gamma \text{ erg s}^{-1}$	L^T/L^γ	$N_{M^\sigma} v $	$F_{16\sigma} v $	Uncertainties
Old Neutron Stars Serendipitous ¹¹	0.3	$\leq 10^{31}$	10^2	$\leq 10^{14}$	$< 2.5 \times 10^{-7}$	Annihilation; L^T/L^γ ; n_*
Old Neutron Stars Background ¹³	0.3	$< 3 \times 10^{30}$	1	$< 3 \times 10^{11}$	$< 7.5 \times 10^{-10}$	ISM; n_* ; L^T/L^γ Annihilation
Old Neutron Stars Background ¹¹	0.3	$< 2 \times 10^{32}$	5×10^3	$\leq 10^{17}$	$< 2.5 \times 10^{-4}$	ISM; n_* ; L^T/L^γ ; Annihilation
Old Neutron Stars Background ¹⁵	0.3	$\leq 10^{32}$	10^3	$\leq 10^{16}$	$< 2.5 \times 10^{-5}$	ISM; n_* ; L^T/L^γ ; Annihilation
Young Neutron Stars (1129+10, etc) ¹⁸	0.3	$< 3 \times 10^{30}$	1	$< 3 \times 10^{11}$	$< 2.5 \times 10^{-6}$	Age; distance; L^T/L^γ ; Annihilation
Neutron Stars Main-Sequence Capture ²⁰	0.3	$< 3 \times 10^{30}$	1	$< 3 \times 10^{11}$	$< 3.5 \times 10^{-11}$	Above, plus main sequence evolution of neutron star
White Dwarfs ²¹	10^{-3}	$\leq 10^{30}$	1	$< 4 \times 10^{19}$	$< 2 \times 10^{-4}$	Annihilation; L^T/L^γ ; internal structure
Earth ²³	10^{-5}	$\leq 10^{20}$	---	$< 2 \times 10^{15}$	≤ 10	Monopole mass; low velocity; capture calculation; nuclear suppression
Jupiter ²³	$10^{-3}-10^{-4}$	$\leq 10^{20}$	---		$< 5 \times 10^{-3}$	nuclear suppression

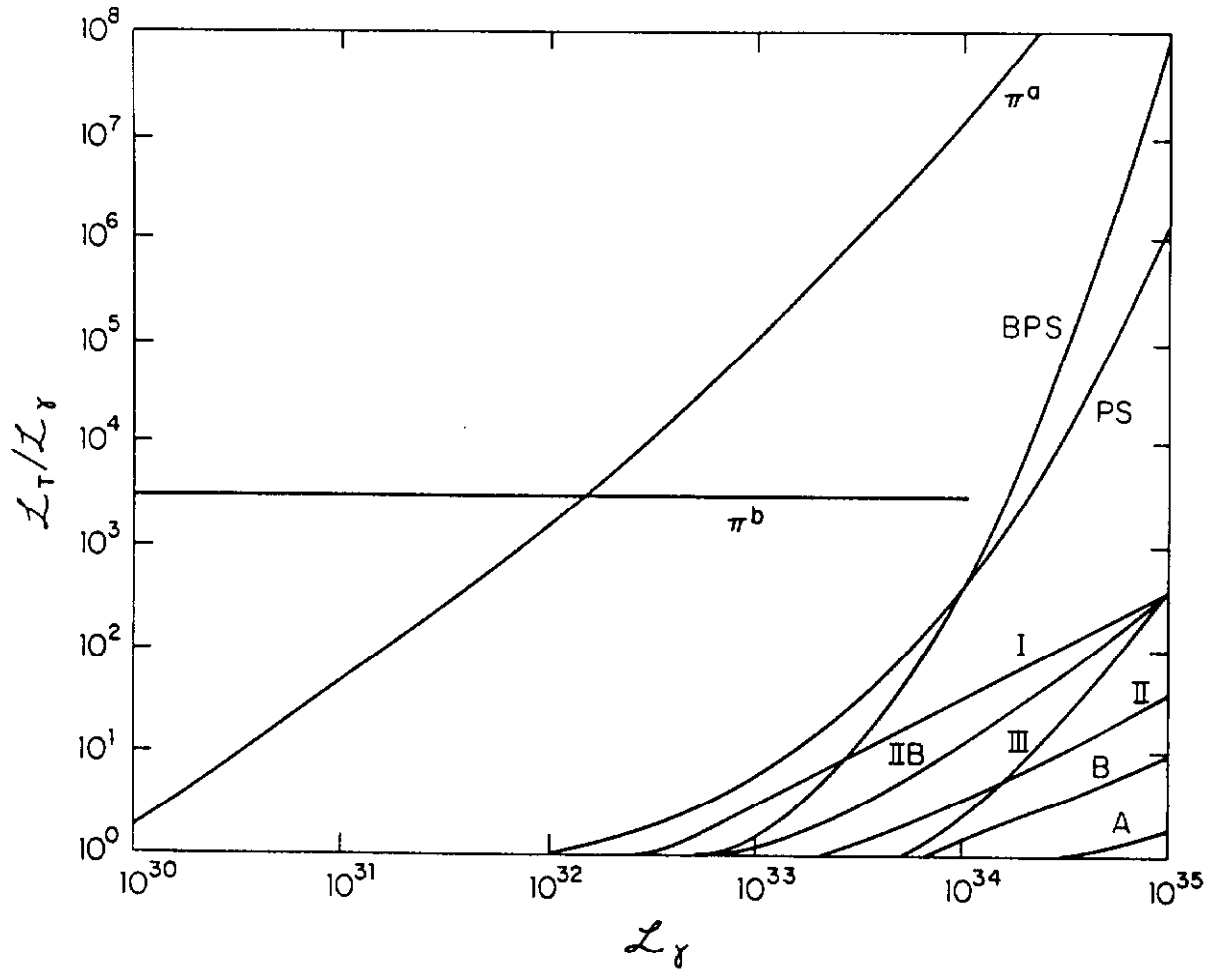


Figure 1. The total (photon + neutrino) luminosity as a function of the photon luminosity. The different curves are for the different neutron star models discussed in ref. 16.

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through the neutron star. However I don't think it is reasonable to assume the only energy loss mechanism is via catalysis.

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